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**Correlation between structural and optical properties of WO₃ thin films sputter
deposited by glancing angle deposition**

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11 **Abstract**

12 Tungsten oxide WO_3 thin films are prepared by dc reactive sputtering. The GLancing Angle
13 Deposition method (GLAD) is implemented to produce inclined columnar structures. The incident
14 angle α between the particle flux and the normal to the substrate is systematically changed from 0
15 to 80° . For incident angles higher than 50° , a typical inclined columnar architecture is clearly
16 produced with column angles β well correlated with the incident angle α according to conventional
17 relationships determined from geometrical models. For each film, the refractive index and
18 extinction coefficient are calculated from optical transmittance spectra of the films measured in the
19 visible region. The refractive index at 589 nm drops from $n_{589} = 2.18$ down to 1.90 as α rises from 0
20 to 80° , whereas the extinction coefficient reaches $k_{589} = 4.27 \times 10^{-3}$ for an incident angle $\alpha = 80^\circ$,
21 which indicates that the films produced at a grazing incident angle become more absorbent. Such
22 changes of the optical behaviours are correlated with changes of the microstructure, especially a
23 porous architecture, which is favoured for incident angles higher than 50° . Optical band gap E_g ,
24 Urbach energy E_u and birefringence Δn_{617} , determined from optical transmittance measurements,
25 are also influenced by the orientation of the columns and their trend are discussed taking into
26 account the disorder produced by the inclined particle flux.

27

28 **Keywords**

29 WO_3 films, GLAD, inclined columns, refractive index, porosity, optical band gap, Urbach energy,
30 birefringence.

1. Introduction

Transition metal oxides represent a very attracting class of materials because of the wide range of physical and chemical properties that they exhibit. Among these oxide compounds, tungsten oxide thin films have been extensively investigated due to their important applications as active layers for electrochromic window devices [1-4], sensors for toxic gases [5-8], optical coatings with high refractive index [9, 10] or transparent and low resistive oxide materials [11, 12]. It is well known that many chemical and physical characteristics of metal oxide thin films are strongly connected to their chemical composition, especially the oxygen-to-metallic concentrations ratio, which can be tuned in order to get a metallic, semi-conducting or insulating behaviour according to the metalloid content in the film [13-16]. However, playing with the chemical composition is not the only approach to tune the properties of metal oxide thin films. The structure at the sub-micrometric scale can also influence the film performances for many applications [17]. So, the design and the growth control of nanostructures in thin layers appear as important issues, e.g. in order to control the optical properties by playing on structural features. To this aim, various strategies have been proposed for the structuration of thin films [18].

In the last decade, the interest of nanostructuration by evaporation and/or sputtering techniques was particularly boosted by the GLancing Angle Deposition (GLAD) method [19]. This method is based on the preparation of thin films on fixed or mobile substrate, with an oblique incidence of the incoming particle flux. Indeed, when the atomic vapour flow comes up at a non normal incident angle α , the nucleation sites intercept the flow of particles. This creates a shadowing effect and there is a tilted grain growth of columnar shape leading to inclined columnar structures with an angle β with respect to the normal of the substrate surface. Nature, crystallography, temperature and surface conditions of the substrate, energy and interactions of the condensed particles with the substrate, among other parameters, have a decisive role in the growth mode of the coating. As a result, the GLAD technique can control the structure of thin films at the micro- and nanoscales. The experimental setup has two degrees of freedom: a rotation axis at an angle α , which allows to vary

the incident angle of the particle flux, and a rotary axis at an angle ϕ (also called azimuth angle), which modifies in an indirect way, the position of the particle source. The produced architectures can be of type i) columnar and inclined; ii) chevron or zigzag by alternating periodically the incident angle of particles from $+\alpha$ to $-\alpha$ maintaining constant ϕ angle (azimuthal angle around the substrate) or with a 180° rotation of ϕ keeping constant α angle; iii) spiral or helical thanks to a continuous rotation of ϕ at a constant incident angle α . This latter type adds to the potential of the GLAD technique. Moreover, changing wisely α and ϕ angles as well as speeds of rotation, more original structures can be obtained such as porous columnar structures with variable diameters [20] or helical columns with squared sections [21]. In the end, the GLAD technique exploits the effects of shadowing created by a tilted substrate relative to normal incidence and a change of the direction of the particle flux through a rotation of the same substrate during the deposition. The two combined can generate different forms of columns and varied architectures. For example, Robbie et al. [22, 23] or Van Popta et al. [24] have deposited by evaporation some structured films with columnar architectures showing sinusoidal, helical and more complex forms. This variety allows envisaging applications in many fields such as biomedical system [25], photonic devices [26], microsensors [27], etc. Moreover thin films deposited by GLAD have high porosity and anisotropic behaviours, which can be used as rugate filters [28], wavelength-selective polarizer [29], or antireflection coating [30].

The purpose of this article is to study the structural and optical properties of the sputter deposited tungsten oxide WO_3 nanostructured thin films grown using various incident angles α of the particle flux from 0 to 80° . We systematically investigate how the structure and optical properties (refractive index, extinction and absorption coefficients, optical band gap, birefringence) of such oriented thin films can be tuned by changing the incident angle of the sputtered particles. The evolution of the porous structure connected to the columnar orientation is especially analyzed in order to discuss and understand some relationships between the architecture of the films and their resulting optical behaviours.

83

84 **2. Experimental details**

85 WO₃ films were sputter deposited by DC reactive magnetron sputtering using a home made system
86 [31, 32]. A tungsten target (5 cm diameter with purity 99.9 at. %) was powered at a constant current
87 density $J = 25.5 \text{ A.m}^{-2}$, with an argon partial pressure $P_{Ar} = 0.1 \text{ Pa}$ and an oxygen partial pressure
88 $P_{O_2} = 0.08 \text{ Pa}$. Substrates (grounded and kept at room temperature) were glass plates and (100)
89 silicon wafers. The distance between the target and the substrate was fixed at 60 mm. The growth of
90 the films was stopped at a thickness close to 1 μm thanks to the calibration of the deposition rate. A
91 systematic change of the incident angle from $\alpha = 0$ to 80° with a 10° increment was performed to
92 tune the inclined columnar structure. Films deposited on glass substrates were characterized thanks
93 to optical transmittance spectra measured with a Lambda 900 Perkin Elmer spectrophotometer in
94 the visible range from 1.55 to 3.10 eV (i.e. wavelength in-between 800 to 400 nm). Refractive
95 index, extinction coefficient and absorption coefficient were determined from interference fringes
96 obtained with experimental optical transmittance spectra using Swanepoel's method [32]. Films
97 prepared on (100) silicon wafers were cross-sectioned and observed by field effect scanning
98 electron microscopy (SEM) using a JEOL 6400 F. WO₃ structures were also characterized by X-ray
99 diffraction (XRD). Measurements were carried out using a Bruker D8 focus diffractometer with a
100 cobalt X-ray tube ($\text{Co } \lambda_{K\alpha} = 1.78897 \text{ \AA}$) in a $\theta/2\theta$ configuration.

101

102 **3. Results and discussion**

103 **3.1 Structural characterization**

104 Tungsten oxide thin films prepared with an incident angle α lower than 50° do not exhibit a clear
105 inclined columnar structure. A densely packed feature is rather observed with a smooth surface
106 topography. However, a further increase of the incident angle (α higher than 50°) leads to a rougher
107 film/air interface and a more defined columnar growth. Observations by SEM of surfaces and cross-
108 sections of WO₃ thin films sputter deposited with an incident angle α of 70 and 80° are shown in

109 figure 1. It is worth of noting that the top of the columns has a rather sharp appearance (Fig. 1a),
 110 which is even more emphasized for $\alpha = 80^\circ$ (surface state becomes irregular and more voided as
 111 illustrated in figure 1c). Such increase of the surface roughness versus incident angle of the
 112 sputtered particles is in agreement with previous investigations focused on metal oxide coatings
 113 produced by GLAD [33, 34]. It is mainly attributed to the shadowing effect at the atomic scale,
 114 which prevails over the surface diffusion of adatoms as the incident angle rises. The structural
 115 anisotropy (formation of growth islands connected to each other by chains perpendicular to the
 116 plane of incidence) previously claimed by Tait et al. [35], is slightly marked for sputtered tungsten
 117 oxide films. The top of the columns appears more or less connected to each other according to the x
 118 direction and perpendicular to the particle flux (Fig. 1a and 1c).

119 Inspection of the cross-sectional view ensures that the GLAD WO_3 films are composed of slanted
 120 columns and inter-columnar voids (Fig. 1b and 1d). The columns are inclined towards the direction
 121 of the incoming vapour flux. The column angle β , defined as the angle between the substrate surface
 122 normal and the long axis of the slanted columns, is measured from the cross-section SEM images.
 123 For incident angle α lower than 50° , the column angle β can not be accurately determined since no
 124 clear columnar growth has been produced but a densely packed structure. For higher angles of
 125 incidence ($\alpha > 50^\circ$), SEM images exhibit morphologies composed by columns and inter-columnar
 126 gaps. The columns become increasingly separated and can easily be distinguished at an incident
 127 angle α of 70° and even more at 80° . The resulting column angles β are 50° and 54° for incident
 128 angles α of 70° and 80° , respectively. Such column angles deviate from the empirical tangent rule
 129 [36], which predicts 53° and 70° , respectively. This rule provides a first order approximation of the
 130 expected β angles. Since the growth can be disturbed by many parameters (temperature, particle
 131 energy, pressure), the tangent rule fails to well describe experimental column angles, especially for
 132 grazing incident angles. This is indeed relevant for thin films deposited by the sputtering process,
 133 where column angles are often lower than those calculated with various ballistic rules [37, 38].
 134 However, our produced WO_3 column angles are in good agreement with relationships proposed by

135 Tait et al. [39]. The sputtering pressure required to maintain the glow discharge restricts the mean
136 free path of the sputtered particles and thus, reduces the shadowing effect. As a result, the
137 theoretical column inclinations predicted by the simple tangent rule is systematically overestimated.
138 Since tungsten oxide thin films have been deposited at room temperature (substrate temperature is
139 lower than 0.3 times the melting point of WO_3 compound), one could expect a poorly crystallized
140 material. However, XRD analyses exhibit diffracted signals (Fig. 2). Peaks corresponding to the
141 WO_3 monoclinic structure are clearly identified for incident angles included between $\alpha = 0$ and 80° .
142 For normal incidence ($\alpha = 0^\circ$), as-deposited films are weakly crystallized since the major diffracted
143 peaks exhibit low intensity and the average crystallite size calculated from the Scherrer equation is
144 smaller than 15 nm. An increase of the incident angle α up to 40° leads to more intense peaks for all
145 crystallographic planes, without any preferential orientation. In addition, the crystallite size reaches
146 30 nm for $\alpha = 40^\circ$ and the diffracted patterns (peaks position, intensity or full-width-at-half-
147 maximum) do not evolve as the incident angle α increases up to 80° . This improved crystallinity as
148 a function of the incident angle has also been observed for other ceramic thin films produced by
149 GLAD [40, 41]. In addition, a reverse effect has been observed by others for some materials [42],
150 showing a reduction of the long range order up to an amorphous structure as the incident angle α
151 rises. As a result, the dependence of crystallinity on the deposition angle has to be considered on a
152 case by case basis and still remains an open question. Nevertheless, it can be correlated with the
153 surface diffusion phenomenon of the sputtered particles. This phenomenon preferentially takes
154 place in the direction of the particle flux, particularly for grazing incident angles. During initial
155 growth and as the incident angle α increases, the formed islands start collecting more adatoms.
156 They will grow faster and tend to capture more incoming vapour flux, reinforcing the growth of
157 large crystallites at the expense of other grains that are consumed during the process. This possible
158 explanation of the long range crystalline order is in agreement with the increase of the crystallite
159 size reported from XRD measurements since grain size rises from 15 to 30 nm as the incident angle
160 α changes from 0 to 40° , and finally 80° .

161

162 3.2 Optical characterization

163 Optical transmittance spectra of tungsten oxide films deposited on glass substrates have been
164 measured in the visible region for various incident angles α of the particle flux (Fig. 3). As expected
165 for WO_3 compound, typical interference fringes are observed. The films deposited by conventional
166 process ($\alpha = 0^\circ$) exhibit the highest amplitudes. For a given wavelength (e.g. 600 nm) the envelop
167 curve is below 70 % for the minimum of transmittance (T_{min}), whereas it is higher than 91 % for the
168 maximum of transmittance (T_{Max}). Amplitude of the fringes is slightly reduced up to an increasing
169 incident angle $\alpha = 40^\circ$. The amplitudes reduction becomes more significant for grazing incident
170 angles, especially for $\alpha = 80^\circ$ since T_{min} is close to 77 % and T_{Max} is 88 % at 600 nm. For this high
171 incident angle of 80° , it is also worth of noting that fringes tend to disappear as the wavelength
172 comes closer to the absorption edge (i.e. between 400 and 500 nm), which can be attributed to the
173 enhancement of the light diffusion. This later is not solely due to structural modification in the film
174 (columns are more inclined), but it also comes from an increased surface roughness for incident
175 angles higher than 40° , as previously observed from SEM analyses (Fig. 1) and in agreement with
176 other theoretical and experimental investigations [43].

177 From optical transmittance measurements of the WO_3 films deposited on glass substrate, refractive
178 index n (Fig. 4) and extinction coefficient k (Fig. 5) have been calculated as a function of the
179 wavelength in the visible region using the Swanepoel's method [44]. The refractive index and
180 extinction coefficient dispersion curves of WO_3 films deposited at various incident angles are all
181 fitted by using the Cauchy dispersion equation in the range of wavelengths 400 to 800 nm. Both the
182 optical index and extinction coefficient follow the Cauchy dispersion evolution as a function of
183 wavelength for any incident angle of the particle flux. WO_3 thin films prepared with a normal
184 incidence of the particle flux ($\alpha = 0^\circ$) exhibit the highest refractive index together with the lowest
185 extinction coefficient. For a reference wavelength of 589 nm, $n_{589} = 2.17$ (and k_{589} is below 1.42×10^{-3}).
186 ³). This value is below that of the bulk WO_3 material since $n_{bulk} = 2.50$ for the same given

187 wavelength [45]. It shows that the films sputter deposited at normal incidence are quite compact but
 188 nonetheless contain significant amounts of defects and voids.

189 A systematic change of the incident angle of the particle flux from 0 to 80° leads to a clear decrease
 190 of the refractive index of tungsten oxide thin films from $n_{589} = 2.17$ down to 1.90, respectively. This
 191 drop becomes very significant when the incident angle is higher than 40°. This effect has already
 192 been observed for other metallic oxide thin films prepared by GLAD [46-48]. It is mainly ascribed
 193 to the growth of a more porous structure versus incident angle. In evaporation or sputtering
 194 processes, the deposited film's planar density is determined by the shadow length and thus, can be
 195 tuned by the incident angle α . Varying the amount of bulk material in the film is a way to change its
 196 refractive index.

197 Similarly, extinction coefficient is nearly constant close to 1.50×10^{-3} at 589 nm up to an incident
 198 angle of 60°. Hence, it remains close to values corresponding to typical dielectric and transparent
 199 compounds. However, for an incident angle of 80° where k_{589} is higher than 4.27×10^{-3} . Such
 200 increase of the extinction coefficient correlates with the increase of the surface roughness
 201 commonly measured for high incident angles. Indeed, the low values of k in the visible region is a
 202 qualitative indication of the good surface smoothness of thin films [49]. Furthermore, the high k
 203 value obtained for $\alpha = 80^\circ$ suggests the presence of marked inhomogeneities in the films (defects,
 204 disordering, oxygen vacancies, surface corrugation), especially a rougher film/air interface favoured
 205 for high glancing angles of deposition.

206 The packing density p and, hence, the porosity π of the WO_3 GLAD films ($\pi = 1 - p$) are significant
 207 characteristics of sputter deposited materials. They can be calculated based on the effective media
 208 approximation, and thus using the mixture rule proposed by Bruggemann [50]:

$$209 \quad \chi_a \left(\frac{\epsilon_a - \epsilon_{eff}}{\epsilon_a + 2 \times \epsilon_{eff}} \right) + \chi_b \left(\frac{\epsilon_b - \epsilon_{eff}}{\epsilon_b + 2 \times \epsilon_{eff}} \right) = 0 \quad (1)$$

210 Where a and b components are randomly distributed in space with volume fractions of χ_a and χ_b ,
 211 respectively ($\chi_a + \chi_b = 1$). The dielectric properties of the medium are described by an effective

212 permittivity ϵ_{eff} , and that of a and b components are ϵ_a and ϵ_b , respectively. For our films, we
 213 considered that a component is the WO_3 bulk material and b component is the vacuum. As a result,
 214 ϵ_{eff} is the permittivity of the film. Assuming that the bulk tungsten trioxide compound has a
 215 refractive index of $n_b = 2.50$ at 589 nm [45] and from the refractive index of the film n_f at 589 nm,
 216 packing density and so, porosity have systematically been calculated and compared to the refractive
 217 index as a function of the incident angle α (Fig. 6). Refractive index and porosity exhibit a reverse
 218 evolution as the incident angle α rises. WO_3 films deposited by conventional incidence ($\alpha = 0^\circ$)
 219 show the highest refractive index with $n_{589} = 2.18$ and thus, the lowest porosity with π lower than
 220 21 %. As expected, index is below that of the bulk material because of the total sputtering pressure
 221 (0.18 Pa) used to deposit the films. Thermalisation effect of the sputtered particles and especially,
 222 intrinsic low energy bombardment in sputtered thin films are both influenced by the sputtering
 223 pressure. They can favour a structure with an open grain boundaries and large columns, leading to a
 224 significant void fraction in the deposited film. As a result, density of WO_3 deposited film is lower
 225 than that of the bulk.

226 It is also worth of noting that refractive index and porosity are nearly constant up to an incident
 227 angle of 50° . Index rapidly drops from $n_{589} = 2.14$ down to 1.78 when α changes from 50 to 80°
 228 whereas the porous structure is enhanced and π reaches 45 % for $\alpha = 80^\circ$. It is mainly attributed to
 229 the shadowing effect, which prevails on the surface diffusion of adatoms increasing the deposition
 230 angle. These results well agree with previous investigations focused on oxide thin films [47, 48].
 231 Varying the amount of bulk material in the film provides a means of tuning its optical properties
 232 according to a monotonic and continuous relationship between n and α . For highly oblique angles
 233 ($\alpha > 80^\circ$), refractive index should approach unity and porosity should tend to 100 %. However, the
 234 lowest index and thus the maximum porosity for WO_3 coatings prepared in this study, obviously
 235 depend on the film preparation conditions, but the measurements techniques (spectrometry in
 236 transmission by Swanepoel's method, ellipsometry) and environment (humidity) can also influence
 237 the reachable index and porosity values.

238 Because of the peculiar architecture of the GLAD thin films, anisotropic behaviours like
239 birefringence can also be expected. Thus, transmittance spectra were measured with two x and y
240 orthogonal directions of incident linear polarized light (T_x and T_y in the x and y directions,
241 respectively and according to axes defined in Fig. 1). The in-plane birefringence is defined as the
242 difference between the two in-plane refractive indices $\Delta n = n_x - n_y$, where n_x and n_y are determined
243 by the Swanepoel's method from T_x and T_y , respectively. Figure 7 illustrates the influence of the
244 incident angle α on the birefringence Δn calculated at 617 nm. This birefringence first increases
245 with the incident angle then reaches a maximum value of $\Delta n = 0.023$ for $\alpha = 50^\circ$. The fact that there
246 is an optimised birefringence was also reported by other authors for ZrO_2 [42], ZnS [48], Ta_2O_5 [51]
247 or TiO_2 [52] films. Furthermore, the value of the maximum Δn can be enhanced using a serial
248 bideposition technique as described by Hodginkson and Wu [51]. For tilted columnar films
249 prepared from standard oblique deposition, the highly porous structure obtained for the highest
250 incident angles does not improve the optical anisotropy. The optimized birefringence can not solely
251 be connected to the porosity, but rather to the biaxial columnar structure. This latter is especially
252 produced for incident angles close to 60° . From simulations and experiments performed by Tait et
253 al. [35], films produce a columnar structure with columns exhibiting an elliptical section versus the
254 incident angle. A structural anisotropy develops parallel to the substrate surface because of the
255 shadowing effect. This effect, mainly in the direction of the incident vapour flux, leads to the
256 formation of growth islands connected to each other by chains perpendicular to the plane of
257 incidence or to the direction of shadowing. The authors established that for an incident angle close
258 to 60° , the shadowing effect prevails on the surface diffusion. By further increasing the α angle, the
259 number of islands falls because of shadowing effect is even more marked. Consequently, the
260 average distance between islands increases. Then, they become disconnected from each other in all
261 directions, resulting in a loss of anisotropy.

262 The Swanepoel's method can also be used to calculate the evolution of the absorption coefficient ξ
 263 as a function of wavelength. Therefore, the optical band gap E_g of WO_3 films can be determined
 264 from the Tauc's relationship according to the following equation [53]:

$$265 \quad \xi h\nu = C(h\nu - E_g)^w \quad (2)$$

266 Where C is a constant and w is 1/2, 3/2, 2 or 3 for transitions being direct and allowed, direct and
 267 forbidden, indirect and allowed, and indirect and forbidden, respectively. The values of optical band
 268 gap energy E_g can be obtained by extrapolating the absorption coefficient to zero absorption in the
 269 $(\xi h\nu)^{1/w}$ against photon energy $h\nu$ plot. According to Hjelm et al. [54], WO_3 compound exhibits
 270 indirect and allowed band gap transitions with $w = 2$. Thus, the E_g value was extracted from $(\xi h\nu)^{1/2}$
 271 versus $h\nu$ plot for WO_3 films prepared with different incident angles (Fig. 8). Without inclining the
 272 particle flux ($\alpha = 0^\circ$), the optical band gap E_g is 3.11 eV. It is higher than that of the WO_3 bulk
 273 material, which is 2.62 eV [55] but in agreement with typical values (more than 3 eV) reported for
 274 tungsten trioxide thin films [56]. This high energy gap of oxide thin films compared to the bulk
 275 value is mainly associated to the small crystallite size (smaller than 15 nm from XRD results in Fig.
 276 2). An increase of the incident angle up to $\alpha = 60^\circ$ does not significantly modify the optical band
 277 gap since E_g slightly decreases down to 3.05 eV. A further increase of the incident angle until $\alpha =$
 278 80° leads to reduce E_g down to 2.90 eV. It can not be ascribed to the improvement of the long range
 279 order since it was shown from XRD analyses that the crystallite size reaches 30 nm for $\alpha = 40^\circ$ and
 280 did not evolve as the incident angle α increased up to 80° (cf. § 3.1). It is rather correlated with an
 281 increase of growth and structural defects, which are favoured for high incident angles. Thus, this
 282 decrease of the optical band gap for incident angles higher than 60° could be interpreted as being
 283 due to more defects in the film, creating more impurity states in the band gap.

284 It is also worth of noting that these structural defects and the short range order both facilitate the
 285 creation of disorder in the material, favouring a tail of density of states. At lower values of the
 286 absorption coefficient ξ , the extent of the exponential tail of the absorption edge is characterized by

the Urbach energy E_u indicating the width of the band tails of the localized states within the optical band gap. It is given by [57]:

$$\xi h\nu = \xi_0 \exp\left(\frac{h\nu}{E_u}\right) \quad (3)$$

Where ξ_0 is a constant. It is obvious that the plot of $\ln(\xi)$ versus $h\nu$ should follow a linear behaviour and allows determining the Urbach energy. This latter was systematically calculated and compared to the optical band gap E_g as a function of the incident angle α (Fig. 9). An increase of the Urbach energy from $E_u = 74$ up to 141 meV corresponds to the decrease in the optical band gap from $E_g = 3.11$ down to 2.90 eV as α rises from 0 to 80°. A linear evolution of E_g versus E_u can be suggested, which is in agreement with past investigations devoted to thin films [58]. It correlates with an improvement of the crystallinity of the films observed from XRD results and corroborates similar linear evolutions previously obtained by others [59] for films going from the amorphous to the polycrystalline structure. A quantitative relationship between the values of E_g and E_u under changes in structural site disorder can be determined with linear coefficients closely linked to structural defects in the materials (bond length, bond angle, chemical disorder) [60]. For our WO₃ GLAD thin films, the increase of the local disorder as the incident angle rises (increase of E_u and reverse evolution of E_g) can be assigned to the secondary grain growth of the voided columnar structure, especially produced for very high incident angles due to a broad incident flux distribution [61]. As a result, the density of defects in the porous structure (e.g. dangling bonds) rises versus the incident angle, leading to higher Urbach energies.

307 4. Conclusion

308 Tungsten oxide WO_3 thin films with inclined columnar structures were prepared by dc reactive
309 magnetron sputtering. The glancing angle deposition technique was implemented to deposit these
310 oriented columnar architectures. Then, a systematic change of the incident angle of the particle flux
311 was performed from $\alpha = 0$ to 80° . A clear columnar inclination was produced for incident angles
312 higher than 50° . The resulting columnar angles were tuned from $\beta = 0$ to 54° leading to an
313 emphasized porous microstructure (45 % of porosity) for the most inclined columns. XRD analyses
314 revealed diffracted signals corresponding to the WO_3 monoclinic structure with an improved
315 crystallinity as the incident angle increased. Similarly, optical properties like refractive index and
316 extinction coefficient were calculated from optical transmittance measurements in the visible
317 region. Refractive index was significantly reduced from $n_{589} = 2.11$ down to 1.90 as the incident
318 angle increased from $\alpha = 0$ to 80° . Extinction coefficient remained nearly constant and close to k_{589}
319 $= 1.50 \times 10^{-3}$ up to $\alpha = 60^\circ$ then became higher than 4.27×10^{-3} for the highest incident angles.
320 Variations of the optical behaviours were correlated to the highly porous structure. Voids separating
321 the oriented columns become more significant for incident angles higher than $\alpha = 60^\circ$ because of
322 the shadowing effect prevailing over the surface adatoms diffusion. Voids and pinholes observed
323 are asymmetric in the x- and y-directions, which introduce anisotropy and birefringence in thin
324 films. The maximum in-plane birefringence was found to be $\Delta n = 0.023$ for an incident angle of
325 50° . A linear and reverse evolution of the optical band gap versus Urbach energy was noticed with a
326 systematic change of the incident angle, which was correlated with an increase of the density of
327 defects in the highest porous structures.

328

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415 **Figure captions**

416 Figure 1

417 Surface and cross-section observations by SEM of WO₃ thin films sputter deposited on (100) Si
418 with two different incident angles α of the sputtered particles: a) and b) $\alpha = 70^\circ$; c) and d) $\alpha = 80^\circ$.
419 Direction of incoming particle flux, incident angle α , column angle β and (x, y, z) axes are
420 indicated. The scale bar is the same for all images.

421

422 Figure 2

423 X-ray diffraction patterns of the tungsten oxide thin films deposited on (100) Si with various
424 incident angles α of the particle flux ($\alpha = 0, 40$ and 80°). Diffracted signals (*) corresponding to the
425 monoclinic WO₃ structure are detected (Si = silicon substrate).

426

427 Figure 3

428 Optical transmittance spectra in the visible range of tungsten oxide thin films deposited on glass
429 substrate for incident angles $\alpha = 0, 40$ and 80° . Clear interference fringes are measured, which are
430 typical of transparent thin films.

431

432 Figure 4

433 Refractive index n as a function of wavelength λ in the visible range for tungsten oxide thin films
434 deposited on glass substrate with incident angles $\alpha = 0, 40, 60$ and 80° . A Cauchy dispersion law
435 was used to fit the evolution of n versus λ .

436

437 Figure 5

438 Extinction coefficient k as a function of wavelength λ in the visible range for tungsten oxide thin
439 films deposited on glass substrate with incident angles $\alpha = 0, 40, 60$ and 80° .

440

441 Figure 6
442 Refractive index n_{589} at $\lambda = 589$ nm and porosity π of WO_3 thin films versus incident angle α .
443 Porosity was determined from the packing density based on the Bruggemann effective medium
444 approximation. Incident angles higher than 50° lead to the most significant changes of the refractive
445 index and porosity. Dashed lines are guides for the eye.

446

447 Figure 7
448 In-plane birefringence Δn at $\lambda = 617$ nm for WO_3 thin films as a function of the incident angle α . A
449 maximum of anisotropy is obtained for an incident angle of 50° . Dashed line is guide for the eye.

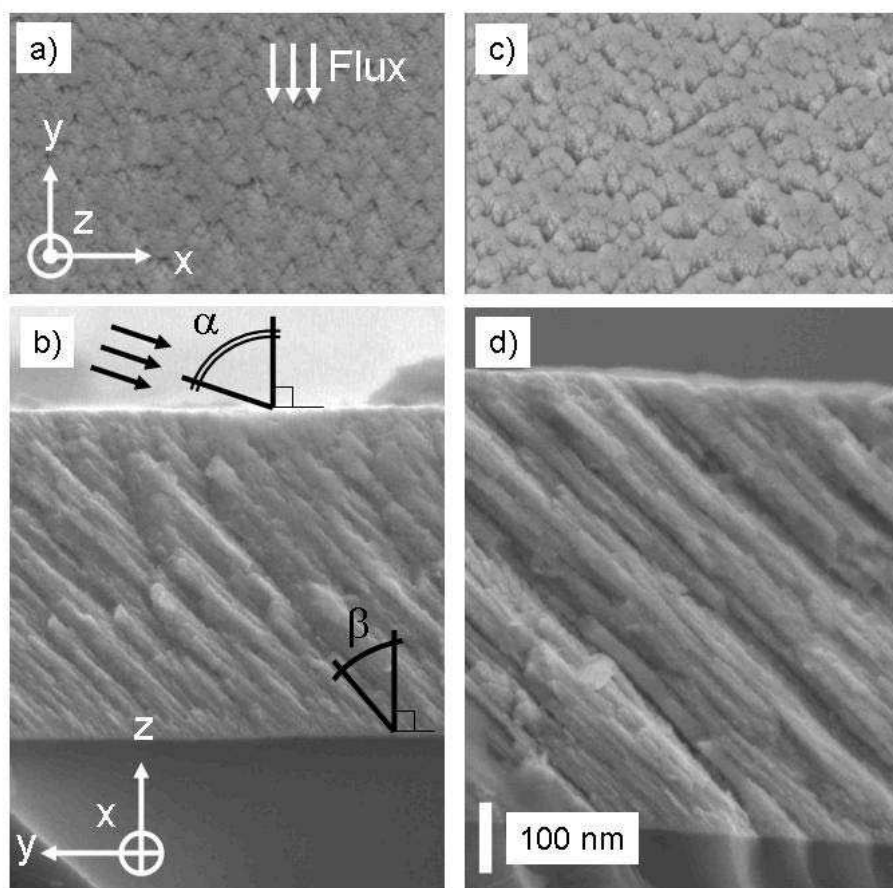
450

451 Figure 8
452 Typical plot of the absorption coefficient $(\alpha h\nu)^{1/2}$ versus photon energy $h\nu$ for WO_3 thin films
453 prepared for incident angles $\alpha = 0, 40$ and 80° . Indirect and allowed transitions were assumed to
454 deduce the optical band gap according to the Tauc's relationship. Solid lines in the figure refer to
455 extrapolation for determining the optical band gap.

456

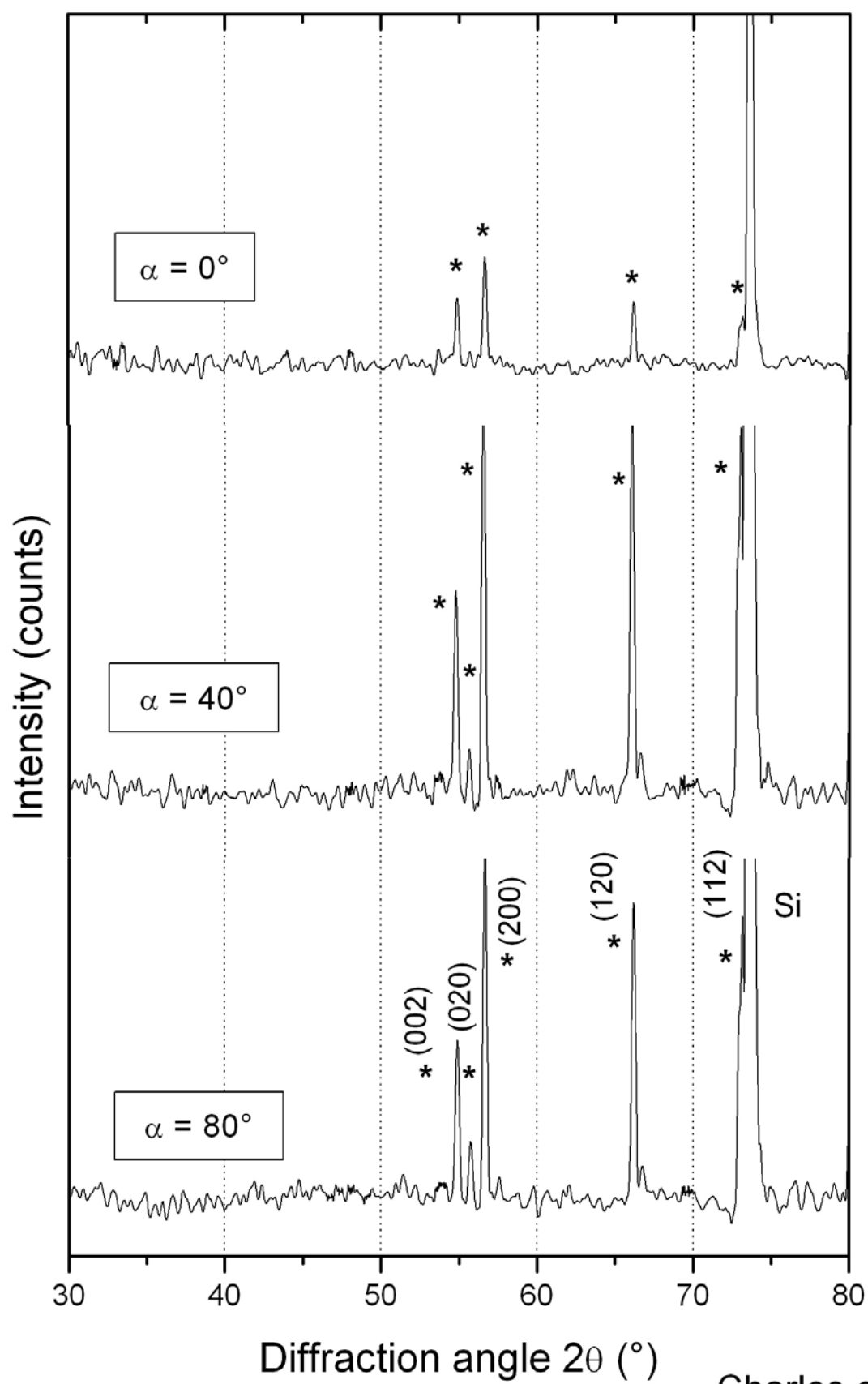
457 Figure 9
458 Linear evolution of the optical band gap E_g as a function of Urbach energy E_u of WO_3 thin films
459 deposited with a systematic increase of the incident angle α from 0 to 80° . Dashed line is guide for
460 the eye.

Figure 1



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Figure 2



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Figure 3

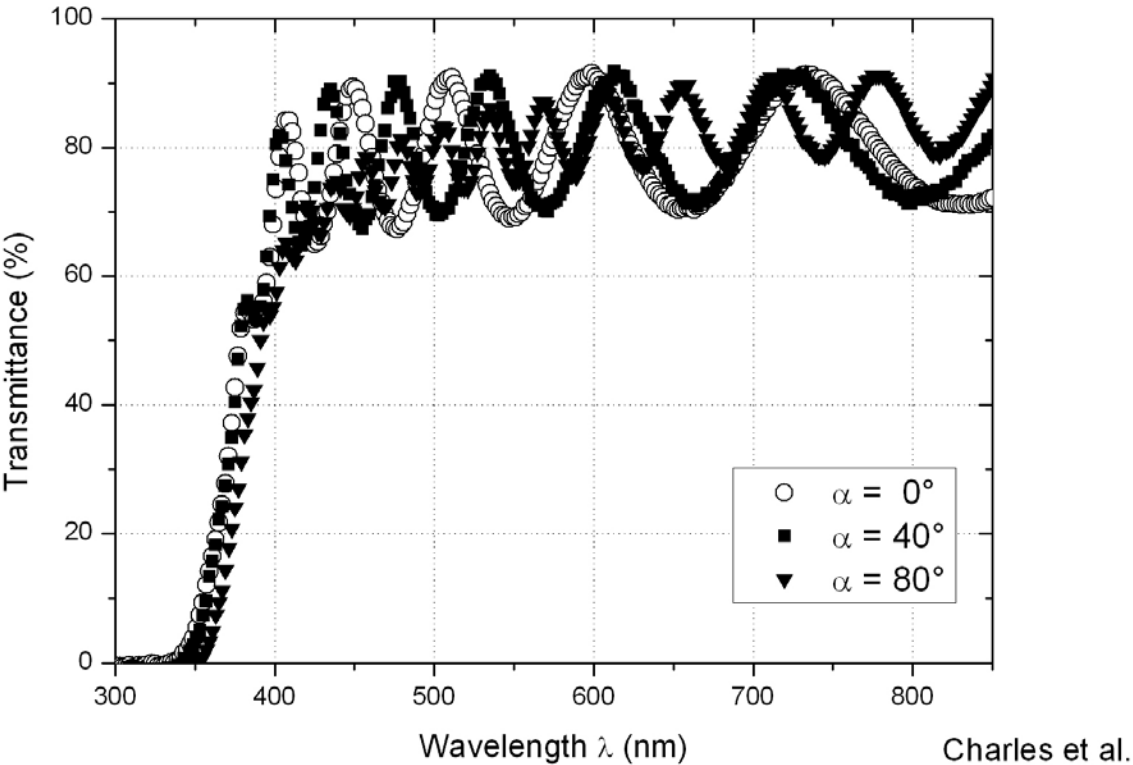
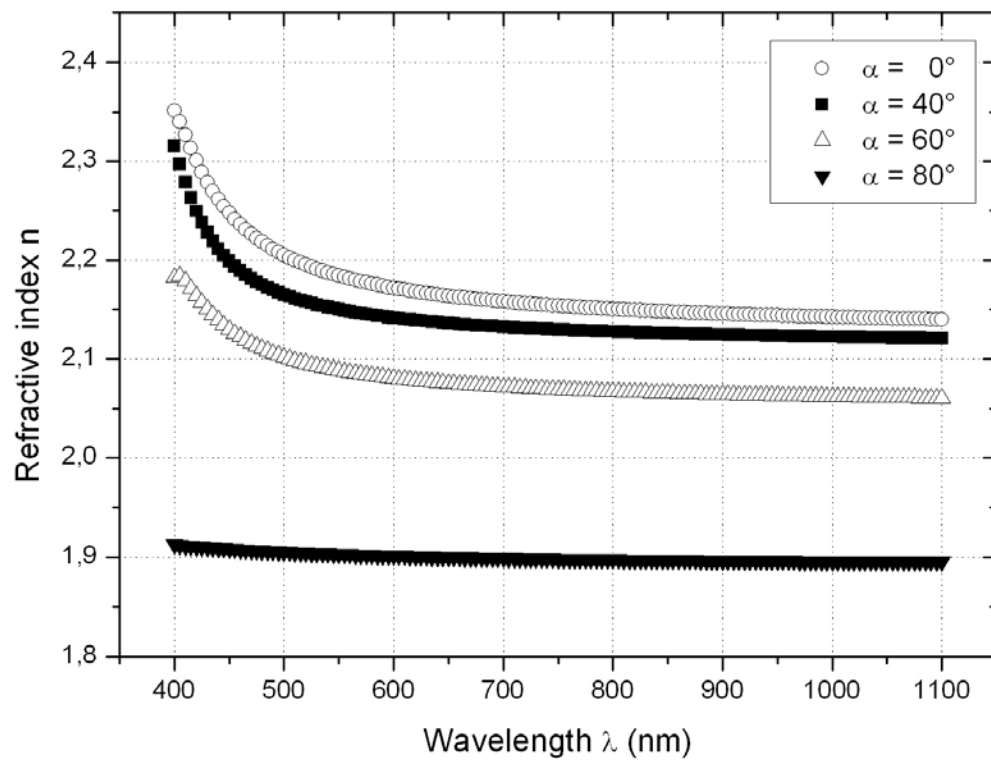
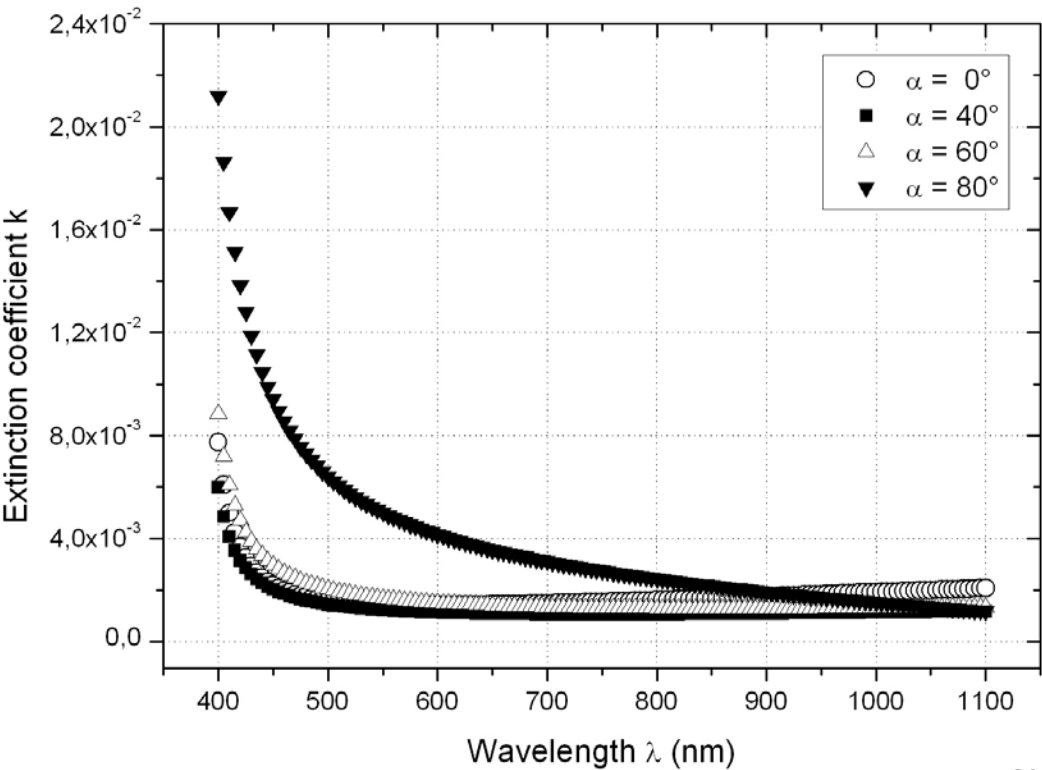


Figure 4



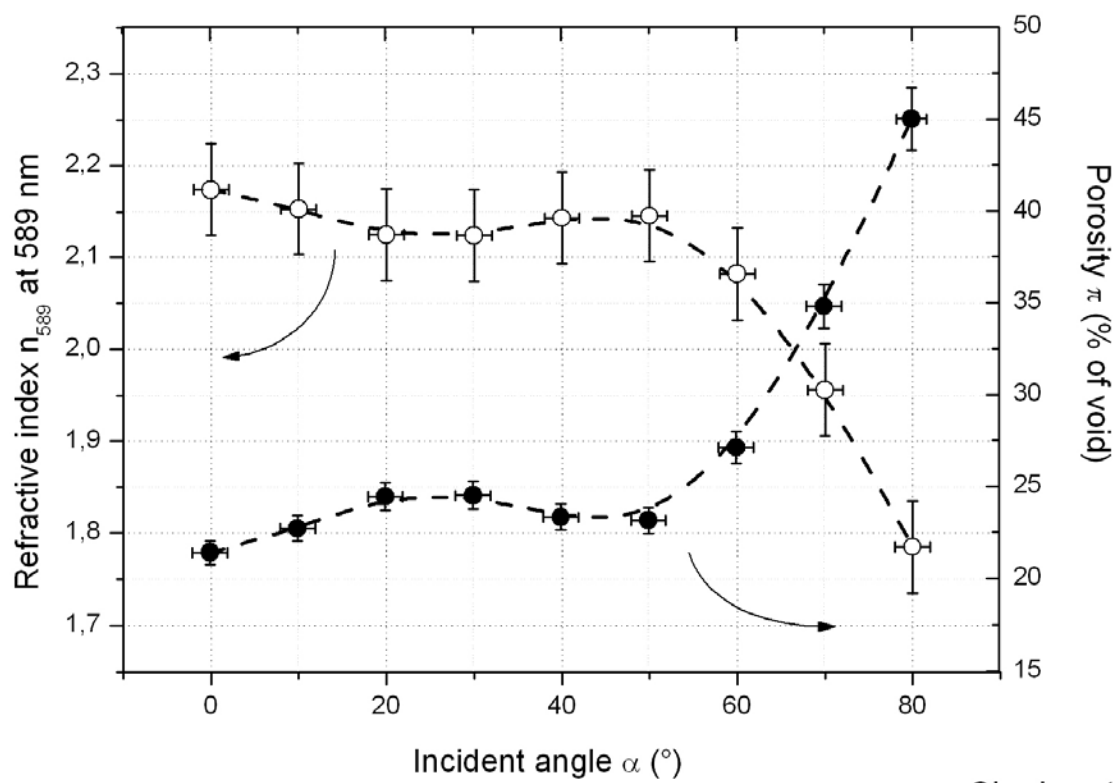
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Figure 5



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Figure 6



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Figure 7

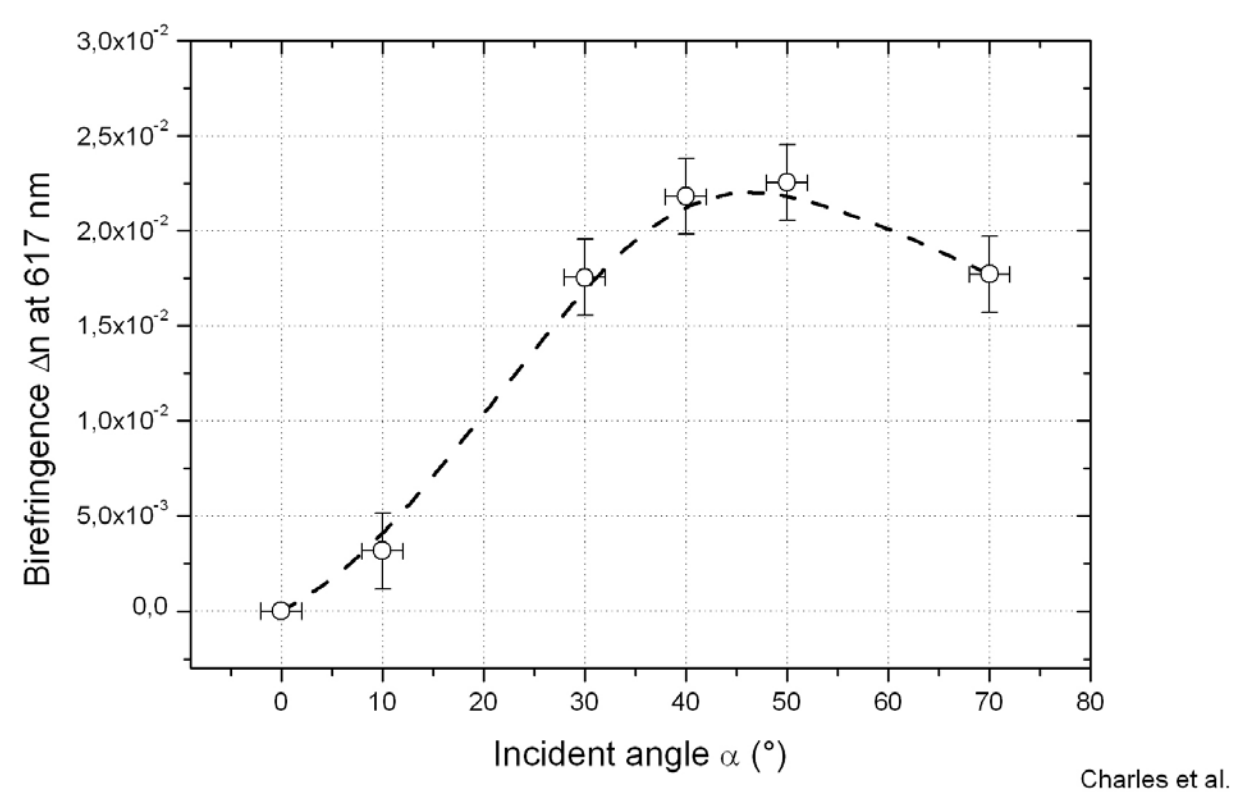
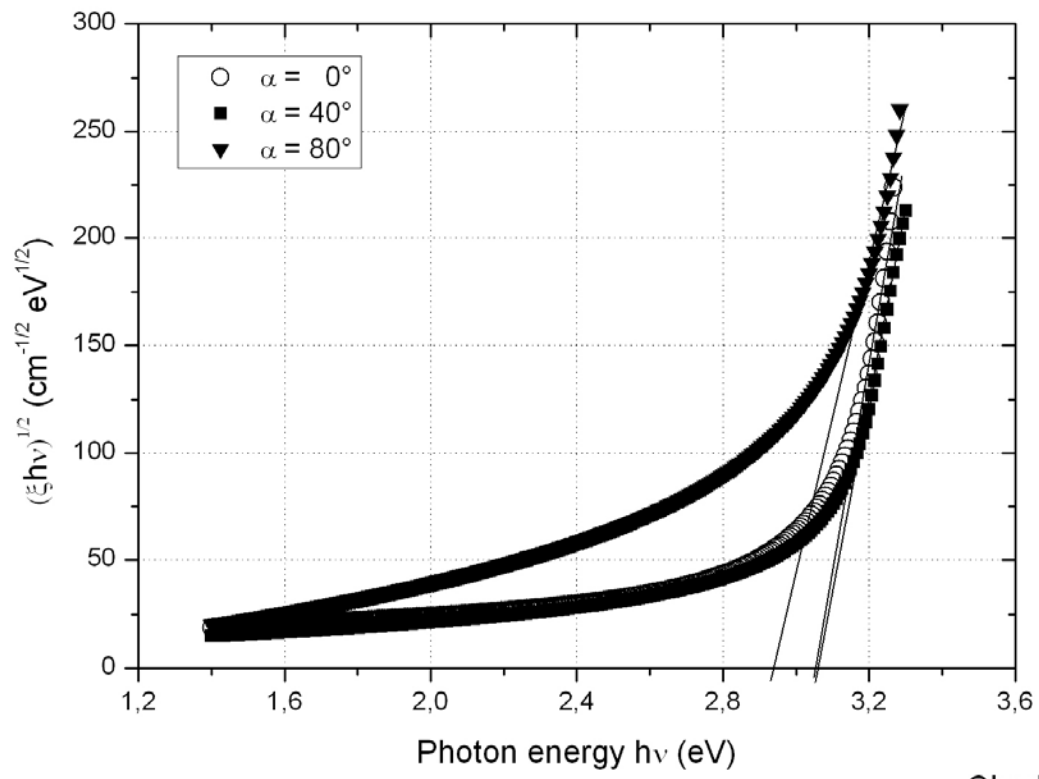


Figure 8



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Figure 9

